FIELD TEST SERIES FOR DEVELOPMENT OF MITIGATION BARRIERS AND ITS DESIGNS AGAINST HYDROGEN EXPLOSION

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ABSTRACT

A field test series where a composite pressure vessel for hydrogen is exploded by fire 1) to provide the facts and the data for the safety distance based on overpressure; 2) to validate the current status of mitigation barrier per KGS FP216 and further designs for developments of the codes and standards relating to hydrogen refueling stations. A pair of barriers to be tested are installed approximately 4 m apart, standing face to face. The explosion source is a type-4 composite vessel of 175 L filled with compressed hydrogen up to 70 MPa. The vessel is in the middle of the barriers and the body part is heated with an LPG burner until it blows out. The incident overpressures from the blast are measured with 40 high-speed pressure sensors, which are respectively installed 2 to 32 m away from the explosion. In the tests with the barrier constructed per the current status of KGS FP216, the explosion of the vessel resulted in partial destruction of the reinforced concrete barrier and made the steel plate barrier dissociated from the foundation then flew away approximately 25 m. The peak overpressure was 14.65 kPa at 32 m. The test data will be further analyzed to select the barriers for the subsequent tests and to develop the codes and standards for hydrogen refueling stations.

NOMENCLATURES

HRS	Hydrogen Refueling Station
RCS	Regulations, Codes and Standards
CHSS	Compressed Hydrogen Storage System
RC	Type of barrier for testing, made of Reinforced Concrete
SB	Type of barrier for testing, made of Steel plate, columns Buried into the foundation
SA	Type of barrier for testing, made of Steel plate, columns fixed to the foundation by Anchors
TPRD	Thermally-activated Pressure Relief Device

1.0 INTRODUCTION

1.1 Motivations

In 2019, hydrogen storage tanks installed for a research purpose in S. Korea were blown up, which resulted in 8 casualties. After the incident, the safety management of HRS has become one of the nation's key strategies in the transition to *hydrogen economy*. Consequently, many efforts have been made by the governments to validate RCSs for safety based on results of real-scale experiments.

Among the safety related facilities for HRS, blast mitigation barrier is the only allowable alternative to the safety distance in case where the code for the distance cannot be met. In S. Korea, the construction of HRS including the barriers should comply with *High-pressure gas safety control act* [1] and its technical standards *KGS FP 216*[2] or *KGS FP 217*[3] (hereinafter, the code). According to the code, the barrier is defined as a structure made of reinforced concrete with the minimum height of 2.0 m and thickness of 120 mm. In some cases, different materials such as a steel plate and a concrete block are also allowed. Despite of those specifications, no evidence has been found that the barrier can provide sufficient protection against explosion of HRS.

In 2007, Remennikov and Rose developed an engineering tool to predict and virtually assess a blast wall by reviewing some previous experimental results and by using a neural network technology[4].

Although it is useful to rapidly assess the reinforced concrete barrier for storage of explosives, the limitation is that the explosion of TNT is only considered as the blast load. From Chi et al. [5] and many other related research, it is known that the overpressure or the blast load decrease by the one third power of distance, implying that the pressure-distance plot shows a linear trend in a log scale.

In this work, the safety performance of the designs of the barriers was experimentally validated by inducing an explosion of CHSS, which simulates the accident in HRS. For the designs to be acceptable for HRS and the codes, the barrier should survive against the explosion, with some cracks but no flying debris, i.e., the structural integrity; and with mitigated overpressure behind it, i.e., the ability to protect. The results of the experiment will do benefit those who find the minimum requirements of the blast mitigation barriers and the safety distance, as well.

2.0 METHODS AND MATERIALS

2.1 Blast mitigation barriers for testing

For the experiment, 3 types of barriers were prepared according to the minimum requirement by the code. While the individual dimensions are given in Table 1, the detailed descriptions are as follows:

● RC is made of reinforced concrete, the strength of which is 40 MPa. In the wall, there is a single layer of wire mesh, radius of 10 mm and mesh size of 40 cm. The wall and the foundation make up a single structure (i.e., a monolith).

● The wall of SB is made of 6-mm thick SS400 plates, fillet welded. The length of stem is 2.4 m, which is longer than the heigh of wall. They are fillet-welded to the back side surface of the plate. The center-to-center distance between adjacent stems is 1,800 mm. The width of 5.4 m means that 4 stems were used in one barrier. The extruded parts of the stems are buried into the reinforced concrete foundation.

● The wall of SA is made of 6-mm thick SS400 plates, fillet welded. The length of stem is 2.0 m, which is equal to the heigh of wall. They are fillet-welded to the back side surface of the plate. The center-to-center distance between adjacent stems is 1,800 mm. The width of 5.4 m means that 4 stems are used in one barrier. The reinforced concrete foundation contains M20 anchors, and the stems are fixed to them with bolts.

The foundations for all types are made of reinforced concrete, strength of 40 MPa, containing a single layer of wire mesh, radius of 10 mm. The curing time was longer than 2 months in the late summer environments.

Due to the limitations of test field, the barriers were constructed in the other place, and then carefully transported approximately 350 km by the trailers before the experiment.

2.2 Explosion source

The explosion source in this experiment which generates overpressure and imposes blast load to the surfaces of barriers is CHSS, heated by an array of LPG jet burner. The CHSS, capacity of 175 L, is a type-4 composite cylinder. Type-4 means the inner liner is a plastic material, fully wrapped with epoxy resin-laden carbon fibres. Disclosure of the dimensions and further information on the CHSS is not permitted by the manufacturers.

Table 1. Dimensions of the barriers fabricated for experiment.

Type	Materials	Thickness	Width	Height	Stem
RC	Reinforced Concrete	120 mm	5 m	2 m	N/A
SB	Steel Plate (SS400)	6 mm	5.4 m	2 m	100 mm, Angled Beam
SA	Steel Plate (SS400)	6 mm	5.4 m	2 m	100 mm, Angled Beam

(a) (b)

Figure 1. Experimental setting for the blast mitigation barrier against the explosion of CHSS

By the manufacture, TPRD in the valve assembly of the CHSS was forcefully disabled. It is a safety device against an exposure to fire; and hence, if it is activated, CHSS won't blow up. The CHSS is filled with compressed hydrogen gas up to 70 MPa by using a gas booster. Since the fueling takes place in an outdoor environment during daytime for 3 days, no chiller is required.

The LPG burner consists of 10-by-16 jet nozzles, which provide a planar heating source, side lengths of approximately 40x80 cm. It is noted that the nozzle is compatible with the technical standards for fire test in UN GTR No. 13. The flames from 40 cm width side can heat approximately one third of the CHSS length in the middle; and the flames from the other side can engulf the cylinder. The surface of CHSS that is not directly in contact with flame is covered with a ceramic blanket for insulation.

2.3 Overpressure measurements

Overpressure induced by the blow-up of cylinder and the consequent explosion of hydrogen is measured by an array of high-speed, pencil-type, incident blast pressure sensors (PCB Piezotronics, Model ICP® 137B23B and 137B24B). The measurement ranges of model 137B23B and 137B24B are 345 kPa (50 psi) and 1,724 kPa (250 psi), respectively. The frequency of measurement for both models is 400 kHz.

Ten rigs are prepared to hold the pressure sensors. A rig is a 5 m long steel pipe, diameter of 10 cm. Four pressure sensors fastened to one rig by screw. The distance between sensors is 1 m. The tips are adjusted such that they aim at the burning CHSS.

2.4 Preparation of experiment

For safety reason, the experiment took place in an open space where TNT is used to be exploded for military training purpose. The ground, diameter of approximately 60 m, is levelled using an excavator. And a square hole of 50 cm in depth and 10 m in length was made. Among the barriers, RC and SB are chosen. They stood in the middle of the square hole, the inner faces confronting each other. The distance between the faces is 4 m. The hole is then filled back with soil. For the barrier SB, the stems are on the back side. Consult Fig. 1(a) for details.

The CHSS is placed such that the axis aims at the centers of the barriers. Using steel wires, the CHSS is firmly fixed on two concrete blocks, approximately 80 cm apart. In this space, the LPG burner is located. In Fig. 1(a), RC is shown on the left; SB is found on the right; and stacks of 4 concrete blocks, 1.8 tons each, are standing on the back of CHSS.

For better understanding the positions of individual units and devices, it is very helpful to introduce a rectangular coordinates system into the test field. The origin is set to the center of the CHSS. Because the height of the barrier is 2 m and the CHSS aims at the middle, the origin is 1 m above the ground. Consulting Fig. 1(a), the x-axis runs in the direction of the barrier RC (left); the y-axis stretches downward; and the z-axis comes out from the paper.

Now, the coordinates of the 10 rigs with 40 pressure sensors can be intuitively summarized into Table 2. From Table 2, the horizontal distances of the rigs from the origin are set to $2(=2^1)$, $4(=2^2)$, $8(=2^3)$, $16(=2^4)$, and $32(=2^5)$. In this way, the pressure data will appear in the log-scale graph with the same interval. The position of the rig No. 9 is the exception. Because the distance between No. 8 and No. 10 is much longer than the others, the authors wanted to put an extra rig. According to the code, KGS FP 216, KGS FP217, and other related regulations, the maximum safety distance for high pressure gas facility is 30 m. Therefore, the maximum distance of the measurement was set 32 m.

The rigs No. 1 to No. 4 are located behind the barrier RC, which reduces the overpressure from the explosion; and the other rigs stand along the y direction where no barrier is placed, and the sensors are exposed to an intact overpressure from the explosion. By comparing these two pressures, the effect of the mitigation barrier can be evaluated.

In Fig. 1(b), a picture taken by a drone is shown to illustrate the overall positions of the rigs for pressure sensors and other devices for the experiment. There are 7 rectangular blocks laid diagonally in a row, i.e., along the y-axis. In addition, there are 4 blocks beyond the barrier RC, i.e., the x-axis. To fix the rigs on the ground, they are first anchored on the concrete blocks, each of them weighs approximate 1.8 tons. The 6-th concrete block on the y-axis does not have a rig. The distance between the origin and the block is 30 m. In an upper right area, another barrier made of steel plate is installed. The hydrogen booster is placed behind the small barrier. The 4 blocks between the barrier and the CHSS are placed to fix the tubing from the booster to the CHSS. The steel hose running diagonally from the upper right corner delivers LPG to the burner.

Table 2. The summary of the coordinates of the 40 blast pressure sensors.

Sensor ID	Rig No.	Coordinate numbers (m)			Sensor ID	Rig No.	Coordinate numbers (m)		
		x	y	z			x	y	z
1	1	2	0	0	21	6	0	4	0
2	1	2	0	1	22	6	0	4	1
3	1	2	0	2	23	6	0	4	2
4	1	2	0	3	24	6	0	4	3
5	2	4	0	0	25	7	0	8	0
6	2	4	0	1	26	7	0	8	1
7	2	4	0	2	27	7	0	8	2
8	2	4	0	3	28	7	0	8	3
9	3	8	0	0	29	8	0	16	0
10	3	8	0	1	30	8	0	16	1
11	3	8	0	2	31	8	0	16	2
12	3	8	0	3	32	8	0	16	3
13	4	16	0	0	33	9	0	24	0
14	4	16	0	1	34	9	0	24	1
15	4	16	0	2	35	9	0	24	2
16	4	16	0	3	36	9	0	24	3
17	5	0	2	0	37	10	0	32	0
18	5	0	2	1	38	10	0	32	1
19	5	0	2	2	39	10	0	32	2
20	5	0	2	3	40	10	0	32	3

3.0 RESULTS AND DISCUSSIONS

3.1 Internal pressure

After fueling the CHSS with hydrogen up to 70 MPa, the LPG burner is ignited and heats the middle part of the CHSS until it blows out. During the experiment, the internal pressure is monitored by a pressure transmitter installed in the tubing and recorded by a datalogger (Graphtec, Model GL840), and the result is drawn in Fig. 2. From Fig. 2, the CHSS is heated for approximately 21 minutes. During this time, the internal pressure continuously increased up to 79 MPa.

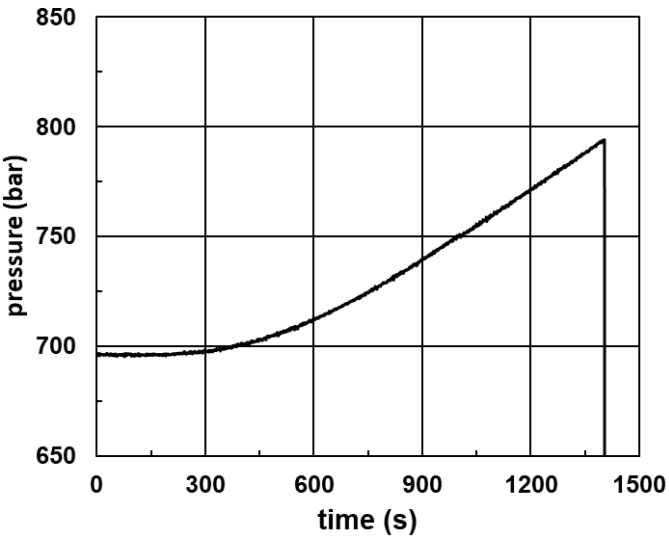

Figure 2. The graph of the internal pressure of CHSS during the experiment

Figure 3 shows the photos taken by a drone hovering 50 m above the ground during the experiment: (a) the CHSS is burned by the LPG burner; (b) a hydrogen fireball is observed by the explosion; and (c) the consequences of the explosion can be seen. The width of the fireball is estimated more than 10 m. When the 3 pictures are compared, the fireball hides the 3rd block. On the left upper corner of Fig. 3(c), the wall of the barrier SB can be found. As a result of the explosion, the steel plate is separated from the foundation and fly over approximately 25 m from where it was. The wall of the barrier RC is not separated from the foundation; however, the top part of the wall slightly moves back. In addition, the stack of concrete blocks located on the back of CHSS slightly moves backward.

(a) (b) (c)

Figure 3. Photos taken by a drone during the test: (a) heating the CHSS; (b) explosion; and the consequences of explosion (steel barrier flew approximately 30 m)

3.2 Damages to barriers

In Fig. 4, the damages to barriers because of explosion are provided for discussion. The LPG burner is found folded near the rig No. 5. Since the burner heats the middle of the CHSS, it is expected that the CHSS is separated evenly into two pieces: one would hit RC; and the other would hit SB. One piece is found near the wall of SB, which means that it flies approximately 25 m and is expected to hit SB; and the other piece is found at the bottom of Fig. 4(a), see near the lowest block. From Fig. 4(a), it can be found that the steel wall of SB is folded in by the CHSS and fly approximately 25 m. Although the foundation does not move, the connections are seriously damaged when 3 stems are pulled out by the explosion, see Fig. 4(b).

(a)

(b) (c)

Figure 4. Experimental setting for the blast mitigation barrier against the explosion of CHSS

Different types of damages are found in the barrier RC. First, the wall is separated from the foundation, but, due to the heavier weight, it does not fly. The top part of the wall moved outward while the bottom is still fixed to the foundation, so that the wall is leaned approximately 20° from the upright position. Many cracks are made across the surface. Some cracks are so deep that, without the wire mesh, the wall would fall. According to the careful observation of Fig. 4(a), a hole can be seen in the middle of the wall. From the close investigation at the site, the hole is elliptical, and the smallest diameter is approximately 40 cm. And the debris are found up to 30 m from the RC.

According to the findings from the experiment, the current minimum requirements do not guarantee the structural integrities of the barriers against the explosion of compressed hydrogen. The debris can do harm on nearby humans and facilities. Improvement should be made to increase the integrity under the recommendations from related experts. For example, the wall thickness of RC barrier should be increased, and the mesh size should be decreased. And the stems of SB barrier should be cross-linked to the foundation.

3.3 Overpressure propagation

The overpressure by the explosion of compressed hydrogen is measured using an array of 40 sensors, see Table 2 for the position of each device. The rigs No. 5 to No. 10 are located along the y-axis. In Fig. 5, the pressure readings from those sensors, the z-coordinate of 3, are present. The noises in the raw data are removed by the rolling-average technique. The positions of the sensors are represented by different colors. The signals transmitted from individual sensors are collected by 5 dataloggers, i.e., 8 sensors to 1 logger. The dataloggers are connected to one computer, so that the times of the measurements are synchronized. In this way, the speed of the overpressure propagation between adjacent rigs can be readily estimated.

According to Fig. 5, the peak overpressure, i.e., the maximum value, exponentially decreases as it propagates outward. The observation is in line with the one-third theory used in the conventional TNT explosion analysis[5]. The speeds of the overpressure propagation, calculated from data between adjacent rigs, are same as approximately 450 m/s. It is greater than the nominal speed of sound in air. The peak overpressure at the rig No. 10, i.e., y=32 m, is 14.65 kPa. Although further study is required to conclude the safety distance, it is generally known that steel structures can be sometimes distorted.

Because the barrier RC is damaged by the explosion, the direct comparisons between the overpressures measured along the x-axis and the y-axis do not provide meaningfully the effect of the mitigation barrier. And thus, the data are not shown in this paper. In addition, the individual overpressure readings are currently under close investigations, and will be published later.

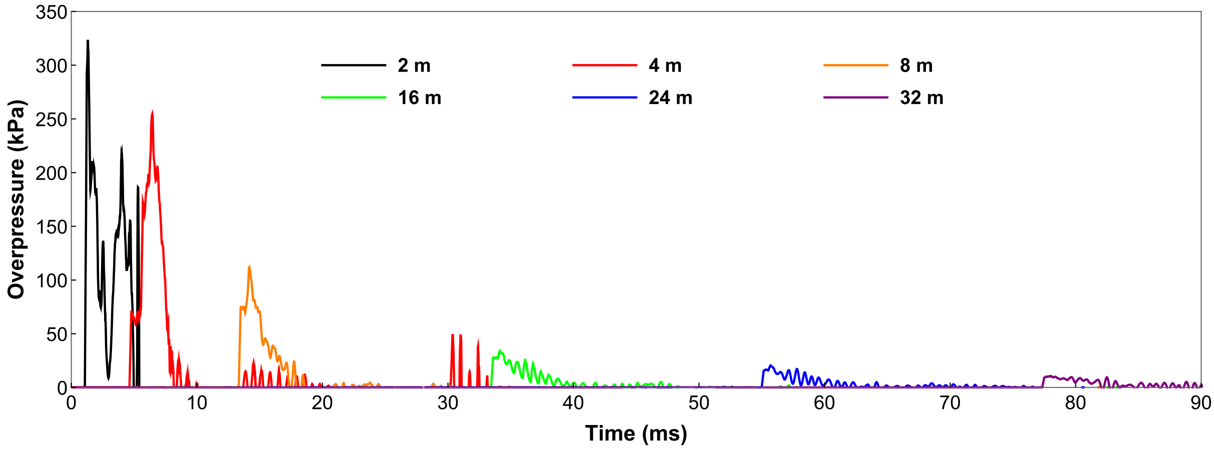

Figure 5. Result of overpressure measurements along the y-axis

4.0 CONCLUSIONS

In this work, the safety performance of the designs of the blast mitigation barriers in hydrogen refueling station is experimentally validated. A field test series where a type-4 composite pressure vessel of 175 L filled with compressed hydrogen up to 70 MPa is exploded by fire while 40 high-speed pressure sensors are monitoring the overpressure across the distance. The test barriers are respectively made of reinforced concrete and steel plate following the minimum requirement of KGS FP216 or KGS FP217. For the designs to be acceptable, the barrier should survive against the explosion, with some cracks but no flying debris, i.e., the structural integrity; and with mitigated overpressure behind it, i.e., the ability to protect. However, the results show that both barriers fail to survive after the explosion: a hole is created on the reinforced concrete barrier with flying debris; and the steel plate wall is separated from the foundation and flies over 25 m. From the overpressure data measured at different distances, the speed of propagation is approximately 450 m/s, greater than the speed of sound in air, and the peak overpressure is 14.65 kPa at 32 m away from the explosion. It is known that, with the overpressure, steel structures in house can be distorted. But detailed analyses are required to conclude the expected damage. Finally, the findings from in this work and further experiments will be used to search the minimum requirements of the blast mitigation barriers and the safety distance for hydrogen refueling stations, and later to revise KGS FP216, KGS FP217 as well as the codes for other high-pressure gases.

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